Developing and Testing a Predictive Model for the Pedestal Height and Width (EPED)

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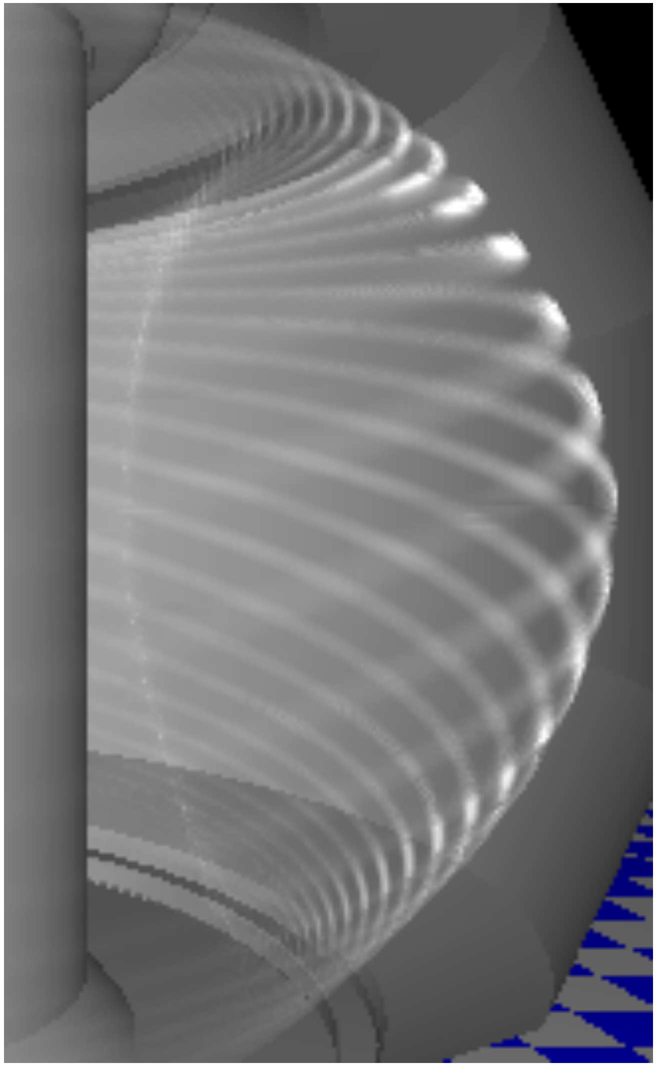

Plasma Edge Theory Workshop
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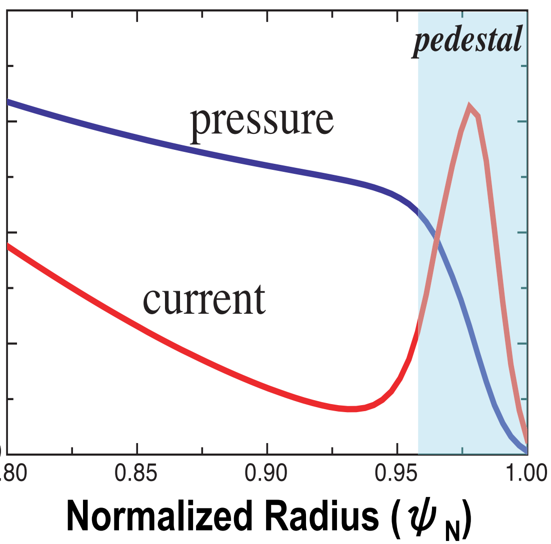
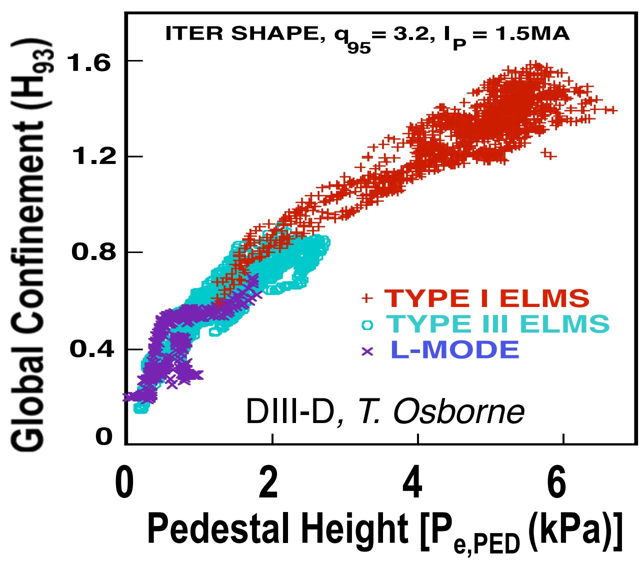
Motivation: Pedestal Height Critical for ITER Performance Prediction and Optimization

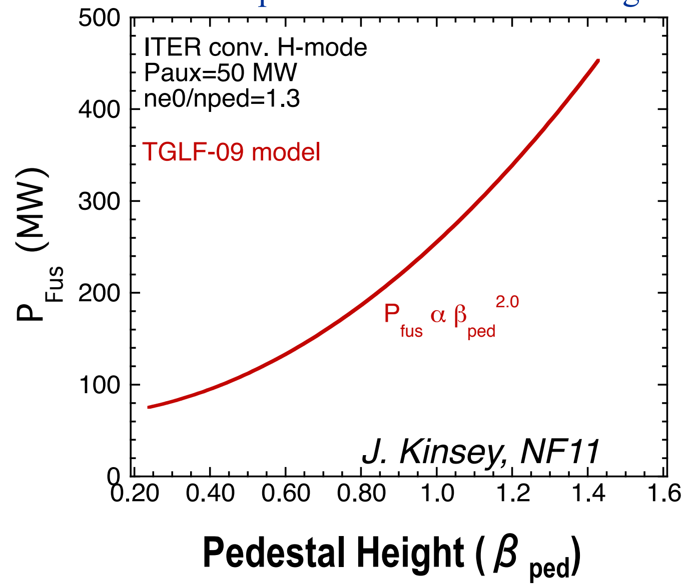
- **High performance ("H-mode") operation in tokamaks due to spontaneous formation of an edge barrier or "pedestal"**
- **Pedestal height has an enormous impact on fusion performance**
  - Dramatically improves both global confinement and stability (observed and predicted)
  - ***Fusion power on ITER predicted to scale with square of the pedestal pressure*** *[Kinsey, NF11]*
- **Accurate prediction of the *pedestal height* is essential to assess and optimize ITER performance, and to optimize the tokamak concept for energy production**



Observed Impact of Pedestal Height



Predicted Impact of ITER Pedestal Height

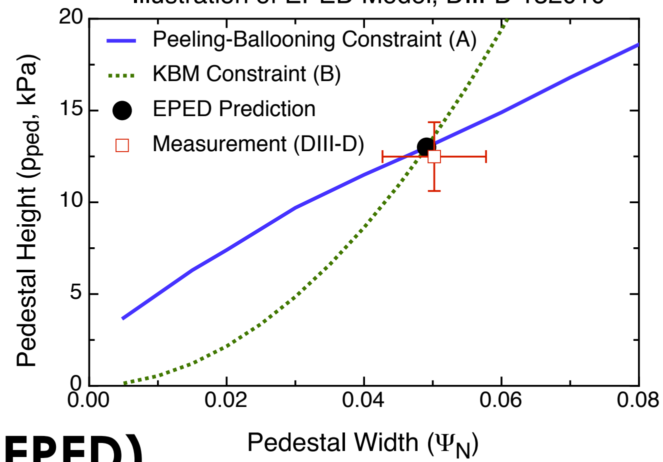


EPED Model Combines Peeling-Ballooning and KBM Physics to Predict Pedestal Height and Width

Develop a model based on two fundamental physics constraints, which are directly calculable, but simple enough to be predictive and easily testable

*P.B. Snyder et al Phys Plas **16** 056118 (2009), NF **49** 085035 (2009), NF **51** 103016 (2011)*

Illustration of EPED Model, DIII-D 132010



A. The Peeling-Ballooning Model

- “Global” constraint on pedestal height vs width
- Successfully tested across wide range of cases

B. Kinetic Ballooning Mode Onset

- Local constraint from ballooning/GK theory
- Integrate to get 2nd relation on width vs height

C. Combine A&B to Develop Predictive Model (EPED)

- 2 “equations” for 2 unknowns: pedestal height and width
- EPED1.6: Both P-B and KBM constraints calculated directly (EPED1 simplified KBM)
  - ***No fitting parameters in any part of model, but still simple & predictive***

D. Validate Model Against Several Devices

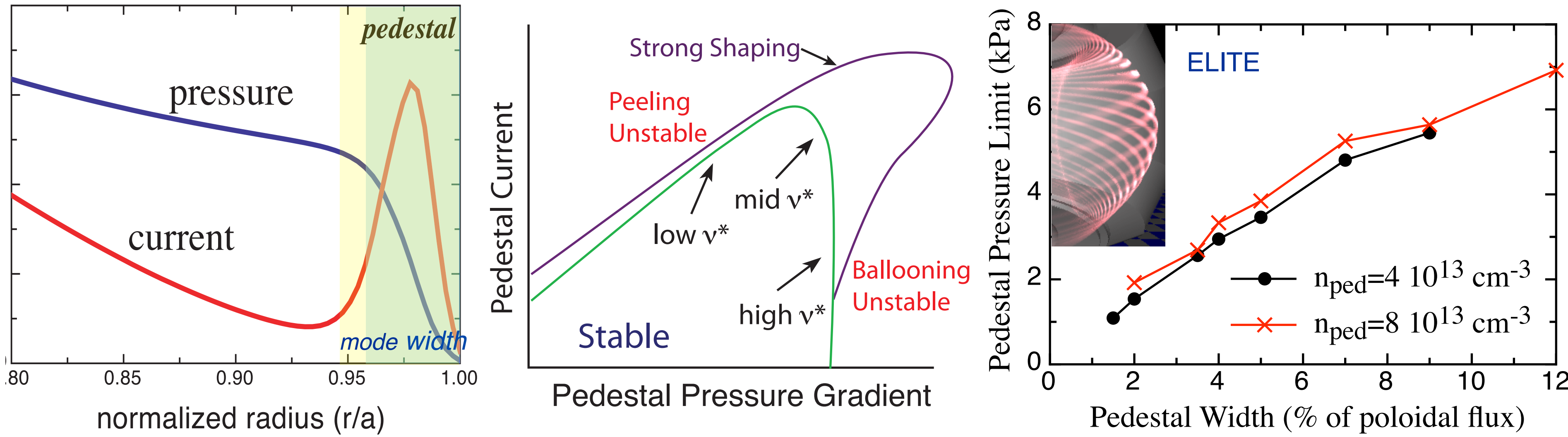
- Comparisons on DIII-D, JET, C-Mod, JT-60U, AUG

E. Application of the EPED Model to RMP ELM Suppression

F. Pedestal Prediction and Optimization for ITER

Peeling-Ballooning Model and Validation

The Peeling-Ballooning Model Explains ELM Onset and Pedestal Height Constraint



- **Pedestal is constrained, and ("Type I") ELMs triggered by intermediate wavelength (n~3-30) MHD instabilities**
  - Driven by sharp pressure gradient and bootstrap current in the edge barrier ("pedestal")
  - Complex dependencies on ν_*, shape etc. due to bootstrap current and "2nd stability"

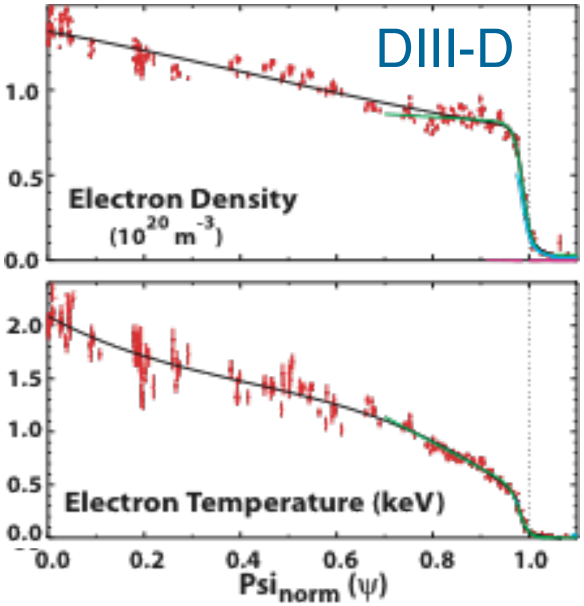
The P-B constraint is fundamentally non-local (effectively global on the scale of the barrier)

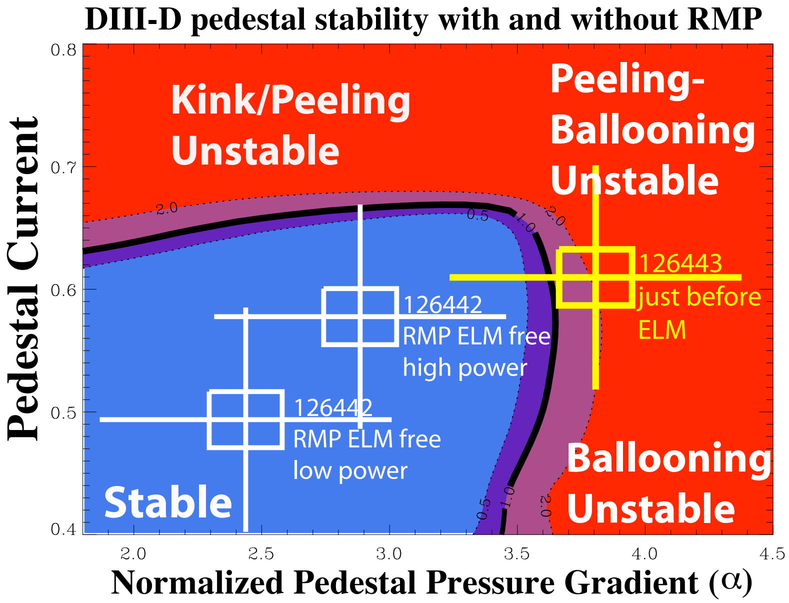
- P-B limit increases with pedestal width (Δ_ψ), but not linearly (roughly β_{Nped}~$\Delta_\psi^{3/4}$)

- **ELITE code, based on extension of ballooning theory to higher order, allows efficient and accurate computation of the intermediate n peeling-ballooning stability boundary**

H.R. Wilson, P.B. Snyder et al PoP ***9*** *1277 (2002). P.B. Snyder, H.R. Wilson et al PoP* ***9*** *2037 (2002).*
P.B. Snyder, K.H. Burrell, H.R. Wilson et al Nucl Fusion ***47*** *961 (2007).*

Peeling-Ballooning Model Extensively Validated Against Observation





- High resolution measurements allow accurate reconstructions and stringent tests of P-B pedestal constraint & ELM onset condition
- Pedestal constraint and ELM onset found to correlate to P-B stability boundary
  [Multiple machines, >200 cases studied, ratio of 1.05 $\pm$ 0.19 in 39 discharges]
- Model equilibrium technique used to apply P-B stability constraint predictively

Can accurately quantify stability constraint [height=f(width)], but need second constraint for fully predictive model of pedestal height and width

Kinetic Ballooning Mode Onset Provides 2nd Constraint

Many mechanisms drive transport across the edge barrier. We hypothesize that the KBM is the mechanism by which the gradients are finally constrained in the presence of strong ExB shear (in the regime of interest to ITER – moderate to low collisionality and standard aspect ratio)

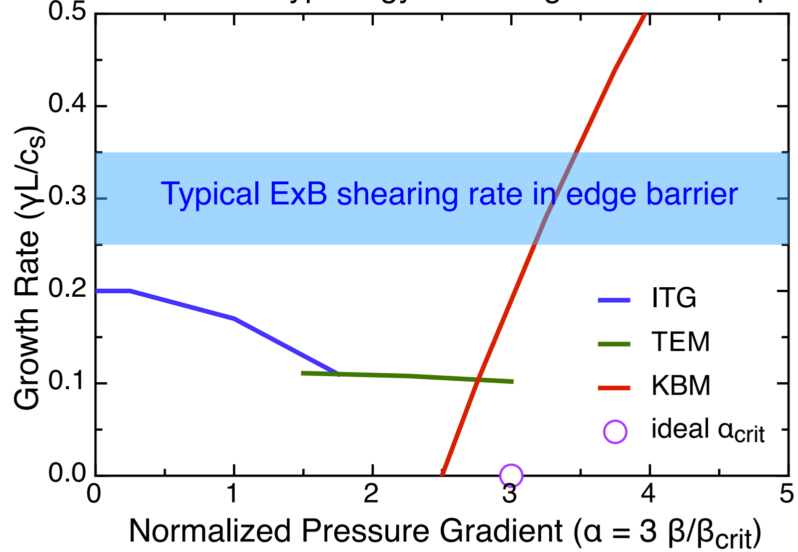
Propose Pedestal Constrained by KBM Onset Near Ideal Ballooning α_{crit}

- **Kinetic Ballooning Mode (KBM) is a pressure gradient driven mode**
  - Qualitatively similar to ideal ballooning mode
  - Kinetic effects essential for linear mode spectrum and nonlinear dynamics
- **Linear studies and electromagnetic KBM turbulence simulations find:**
  [Rewoldt87,Hong89,Snyder99,Scott01,Jenko01, Candy05…]
  - Abrupt linear onset, quickly overcomes ExB shearing rate, large QL transport
    - Linear onset near ideal ballooning critical gradient due to offsetting kinetic effects
  - Nonlinear: very large fluxes and short correlation times (highly stiff)
    - Flux will match source at gradient near critical

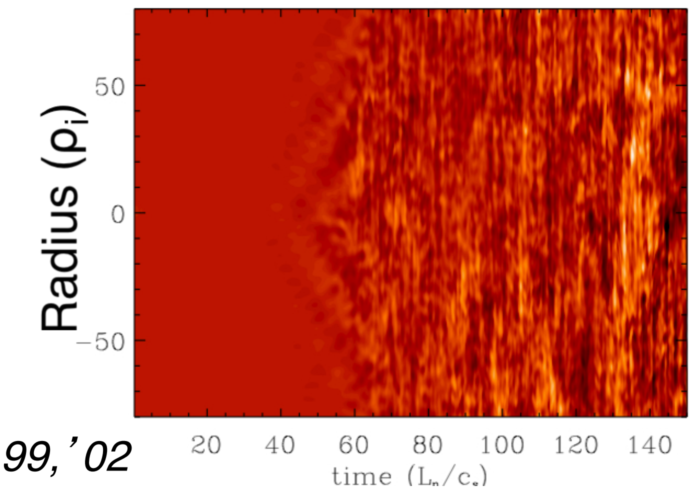
➢ **Simple model of the KBM can be quantitatively accurate** (standard aspect ratio, low to mid collisionality)

- Stiff onset near MHD ballooning criticality

Cartoon of typical gyrokinetic growth rate vs β



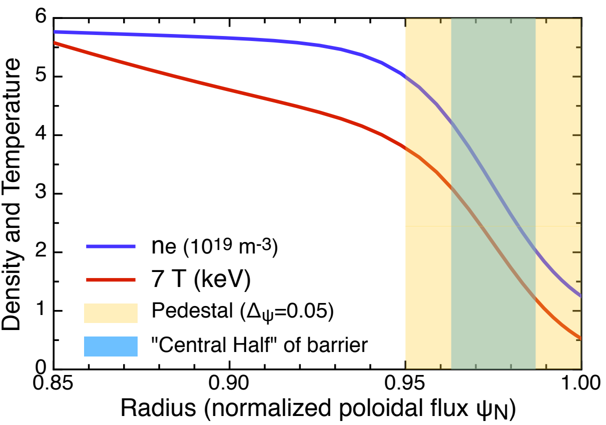
Kinetic Ballooning Mode, β=1%



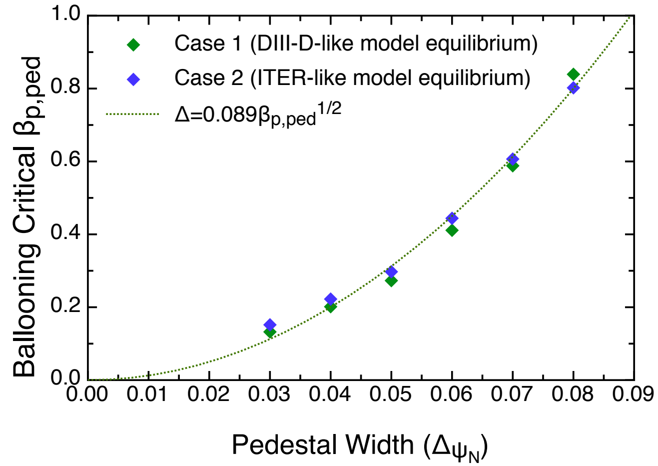
Snyder'99,'02

Calculate KBM Constraint in Terms of Measurable Parameters "ballooning critical pedestal"

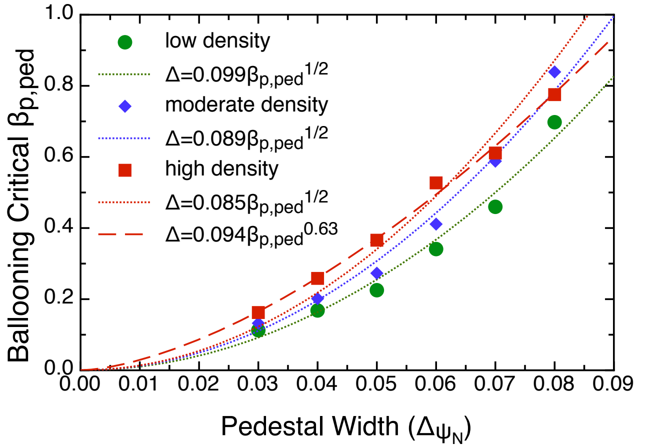
Model Profiles and Definition of Central Half of Edge Barrier



Calculated KBM Constraint using BCP Method



Variation of KBM constraint (BCP method) with collisionality



"Ballooning critical pedestal" calculations to quantify KBM constraint

- Model equilibria used to integrate local KBM constraint
- "ballooning critical" when central half of edge at or beyond MHD critical gradient *[baloo code, R.L. Miller]*
- Find expected dominant dependence: $\beta_{p,ped} \sim \Delta_{\psi_N}^2 \Rightarrow \Delta_{\psi_N} \sim \beta_{p,ped}^{1/2}$
- Lump weak dependencies into G function, calculate <G>~0.07-0.1 for standard aspect ratio tokamaks (0.084 ± 0.10 for ensemble of 16 cases), collisionality dependence

$$\boxed{\Delta_{\psi_N} = \beta_{p,ped}^{1/2} G(\nu_*, \varepsilon \ldots)}$$

EPED1.6: Directly calculate for each case
EPED1: Simplified, <G>=0.076

KBM constraint consistent with many observations, eg Z. Yan PRL11, Groebner10, Snyder09

GENERAL ATOMICS

Implementing and Testing the EPED Model

Mechanics of the EPED Predictive Model

- **Input: B_t, I_p, R, a, κ, δ, n_{ped}, β_{global}, m_i**
- **Output: Pedestal height and width** ***(no free or fit parameters)***

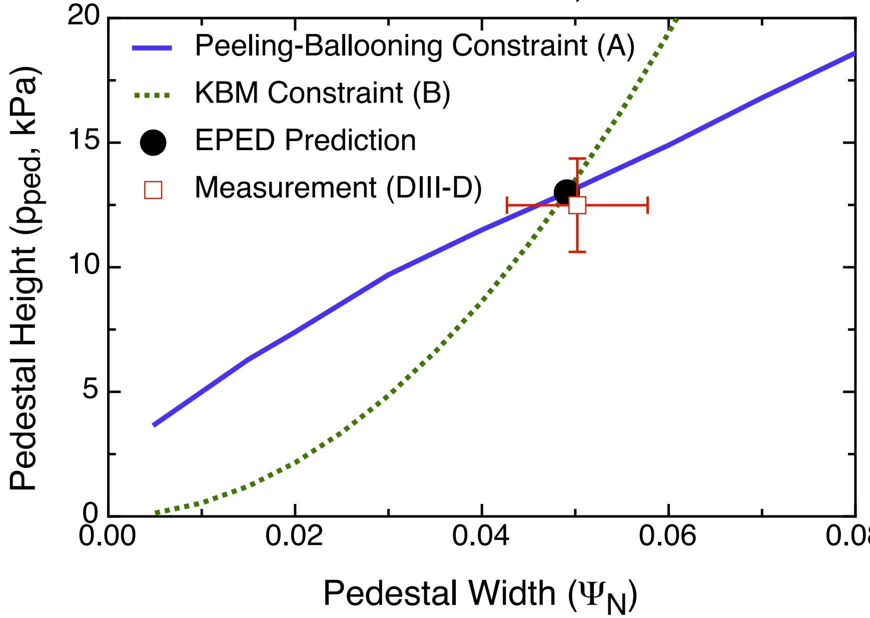
A. P-B stability calculated via a series of model equilibria with increasing pedestal height

- ELITE, n=5-30; non-local diamag model from BOUT++ calculations

B. KBM Onset: $\Delta_{\psi_N} = \beta_{p,ped}^{1/2} G(\nu_*, \varepsilon \ldots)$

- Directly calculate with ballooning critical pedestal technique

Illustration of EPED Model, DIII-D 132010



P.B. Snyder et al Phys Plas ***16*** *056118 (2009), NF* ***49*** *085035 (2009), NF* ***51*** *103016 (2011)*

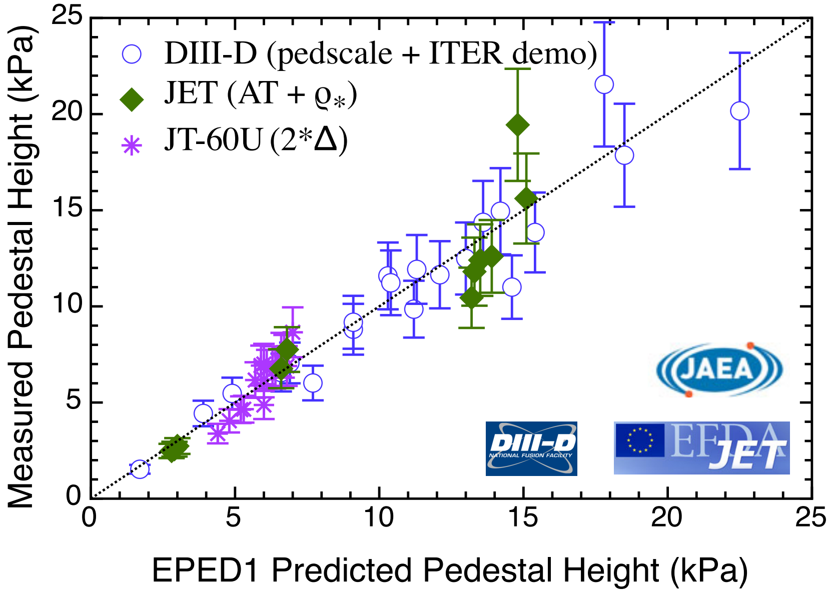
- **Different width dependence of P-B stability (roughly $p_{ped} \sim \Delta_\psi^{3/4}$) and KBM onset ($p_{ped} \sim \Delta_\psi^{2}$) ensure unique solution, which is the EPED prediction (black circle)**

  -can then be systematically compared to existing data or future experiments

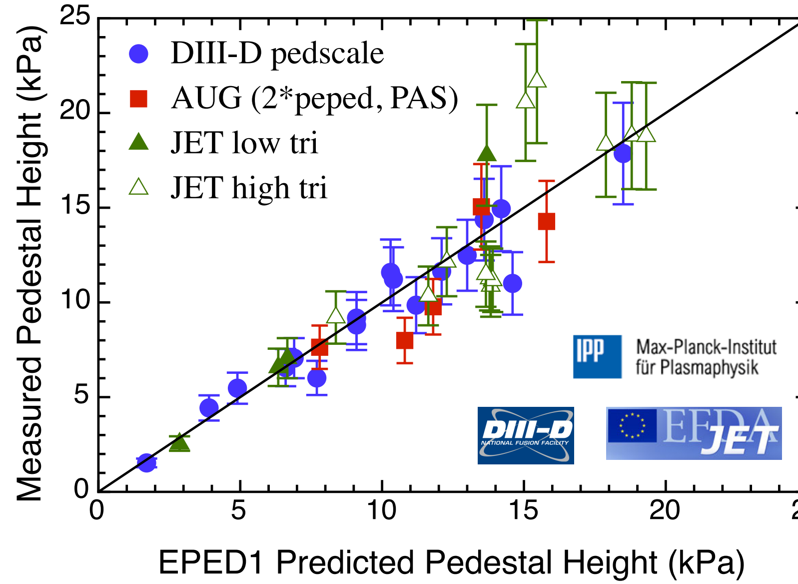
P-B stability and KBM constraints are tightly coupled: If either physics model (A or B) is incorrect, predictions for both height and width will be systematically incorrect

Effect of KBM constraint is counter-intuitive: Making KBM stability worse increases pedestal height and width

Successful Tests of EPED1 on Multiple Devices



P.B. Snyder et al, Nucl Fusion 2009

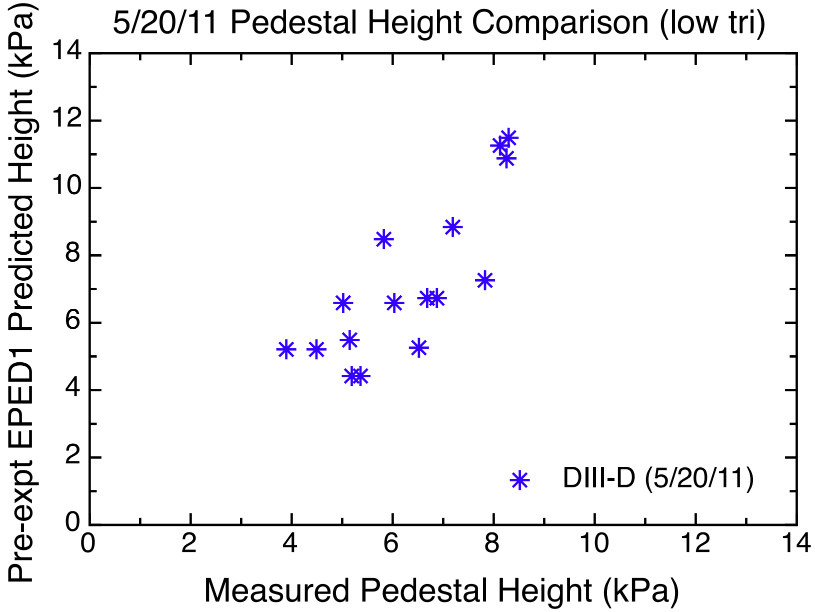


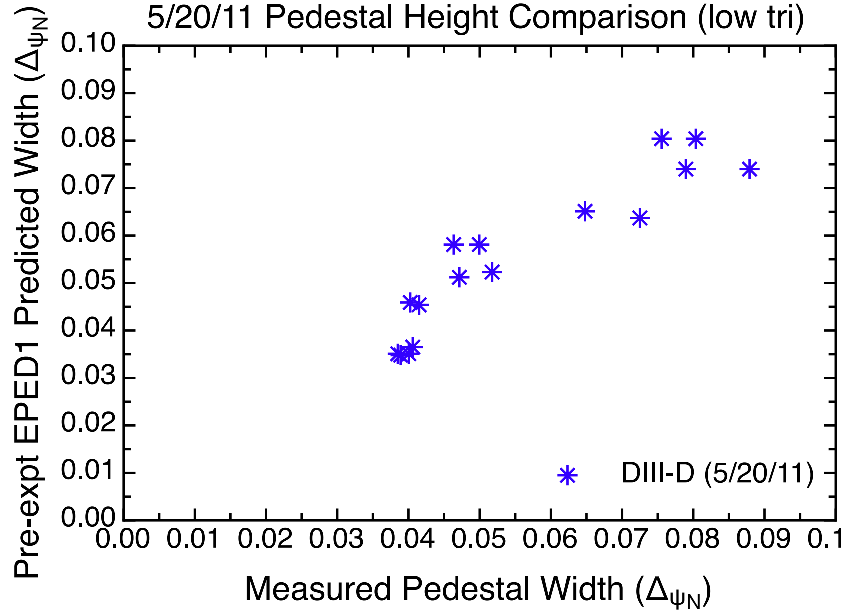
M Beurskens et al, Phys. Plasmas 2011

Simplified EPED1 model is relatively efficient (1-10 hrs of CPU, ~500 ELITE calculations, per case), and allows easy use on large data sets and predictions before experiments

- *21 DIII-D, 16 JT-60U, 11 JET cases:* Predicted/Measured pedestal height= 1.02 ±0.14 *(left)*
- Dimensionless ρ_* scaling study *[Beurskens, Osborne, Wolfrum et al 2010]* found similar agreement on a set of JET, AUG and DIII-D discharges

EPED1 Used to Predict Pedestal Height and Width Before Experiments (2011 DIII-D I_p scan)





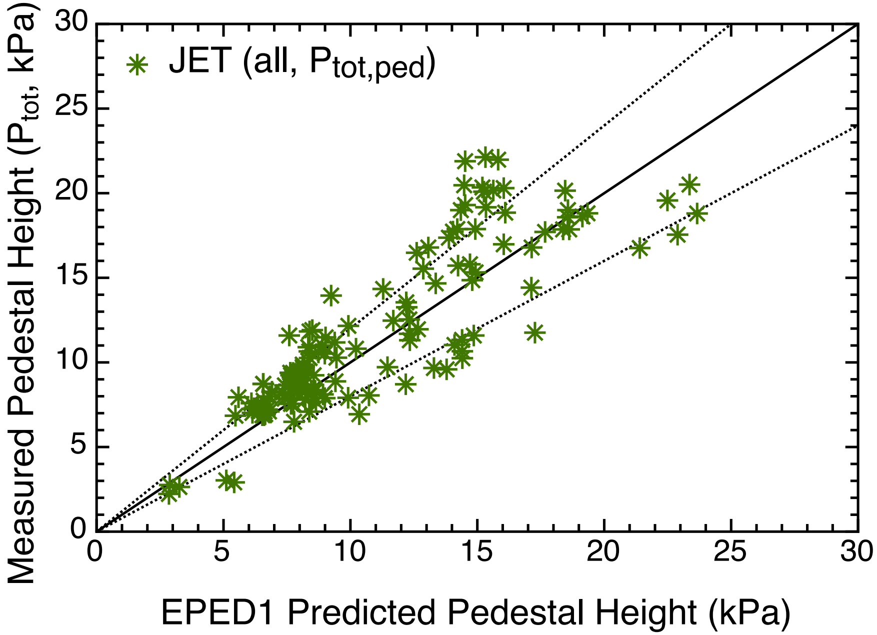
Preliminary: EPED1 predictions made and presented before the expt and use planned parameters, not achieved, and data is from control room analysis

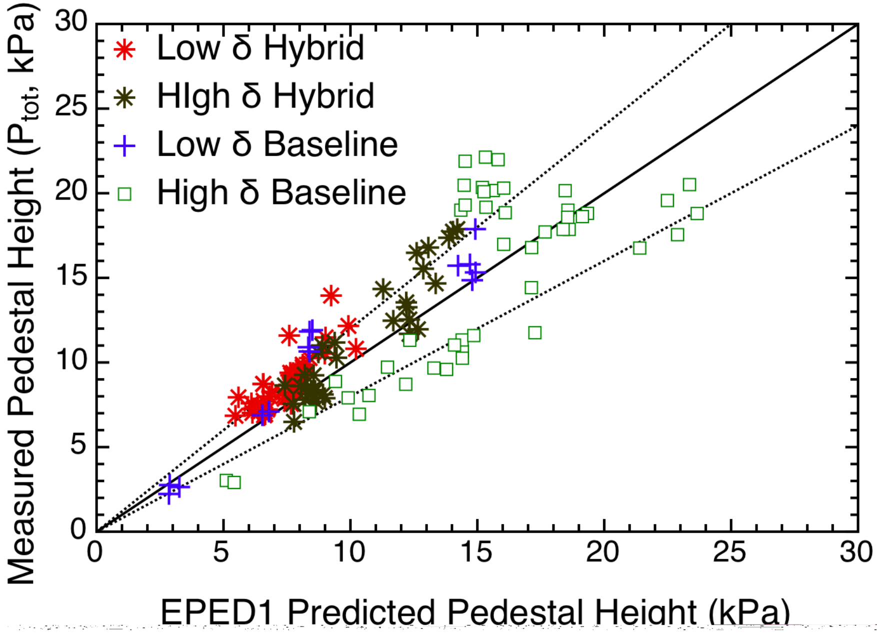
Achieved good range of widths, with several at wide values (>~0.06)

Initially good agreement with EPED1 model (16 cases, 9 shots):

- Ratio of predicted to observed pedestal height: 1.13 ± 0.22, corr=0.81
- Ratio of predicted to observed pedestal width: 1.00 ± 0.13, corr=0.93
- Ratio of predicted to observed pedestal average pprime: 1.13 ± 0.16, corr=0.96

Test of EPED1 on Full JET Dataset (137 cases)





Snyder et al TTF11, Beurskens et al ITPA11

Ratio of predicted to observed height = 0.97 ± 0.21 (corr *r*=0.86)

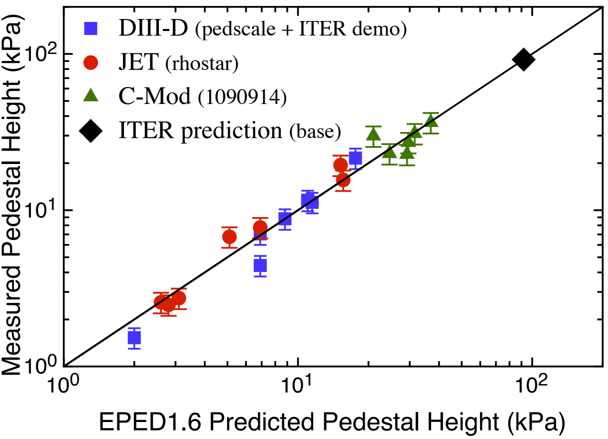
For the 137 point comparison, the correlation between the EPED1 model and measurements (0.86) is consistent with:

- ~15% uncertainty in measurement and model, ~20% uncertainty in measurement and ~10% uncertainty in model, ~10% measurement uncertainty and ~20% in model

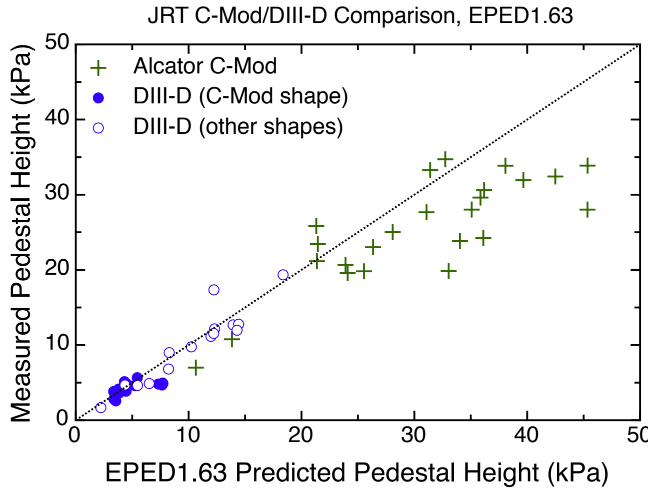
EPED1 model accurate to ~20% overall with strong correlation between predicted and observed pedestal height (no adjustable parameters), similar for different types of shots

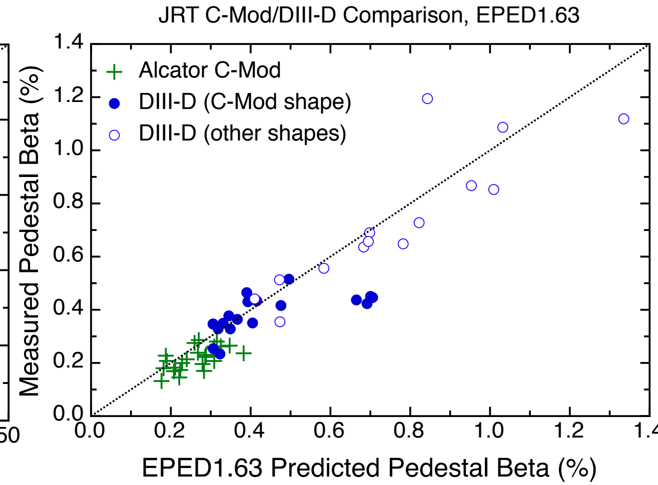
GENERAL ATOMICS

Test of the Full EPED1.6 Model on C-Mod, DIII-D and JET



*P.B. Snyder et al NF **51** 103016 (2011)*





Full EPED1.6 model calculates both P-B and KBM constraints directly for each case – more time consuming, but more precise

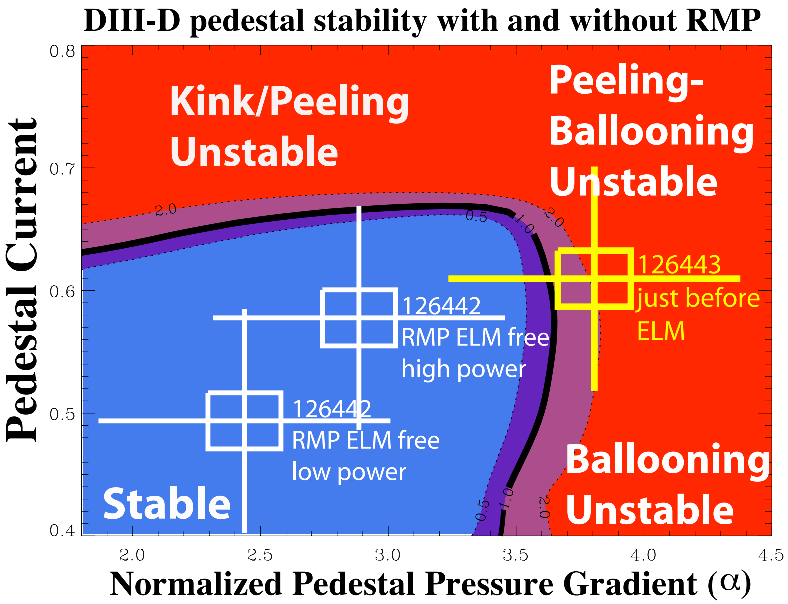
- Advanced model of diamagnetic effects particularly important for comparisons with Alcator C-mod
- Prior comparison (left) found good agreement with C-Mod, DIII-D, JET

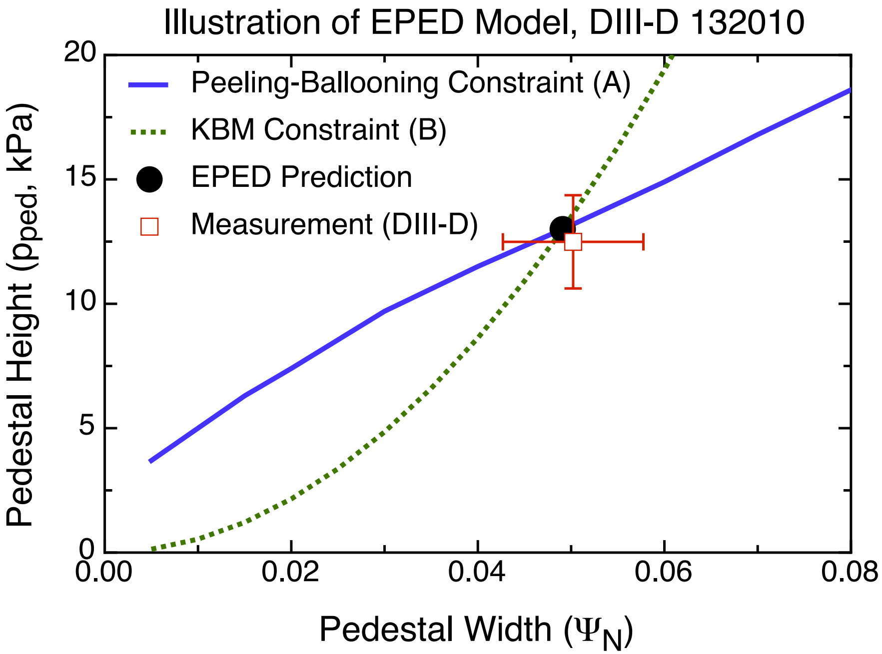
2011 US Pedestal Milestone: Joint C-Mod/DIII-D similarity experiment

- Ratio of predicted to observed height 1.15 ± 0.23, corr=0.96, 59 cases (C-Mod using ELM-averaged pedestal height, so expect predictions to be slightly high)
- Good match in pedestal beta achieved by operating DIII-D in C-Mod shape

Using EPED to Understand RMP ELM Suppression (low collisionality)

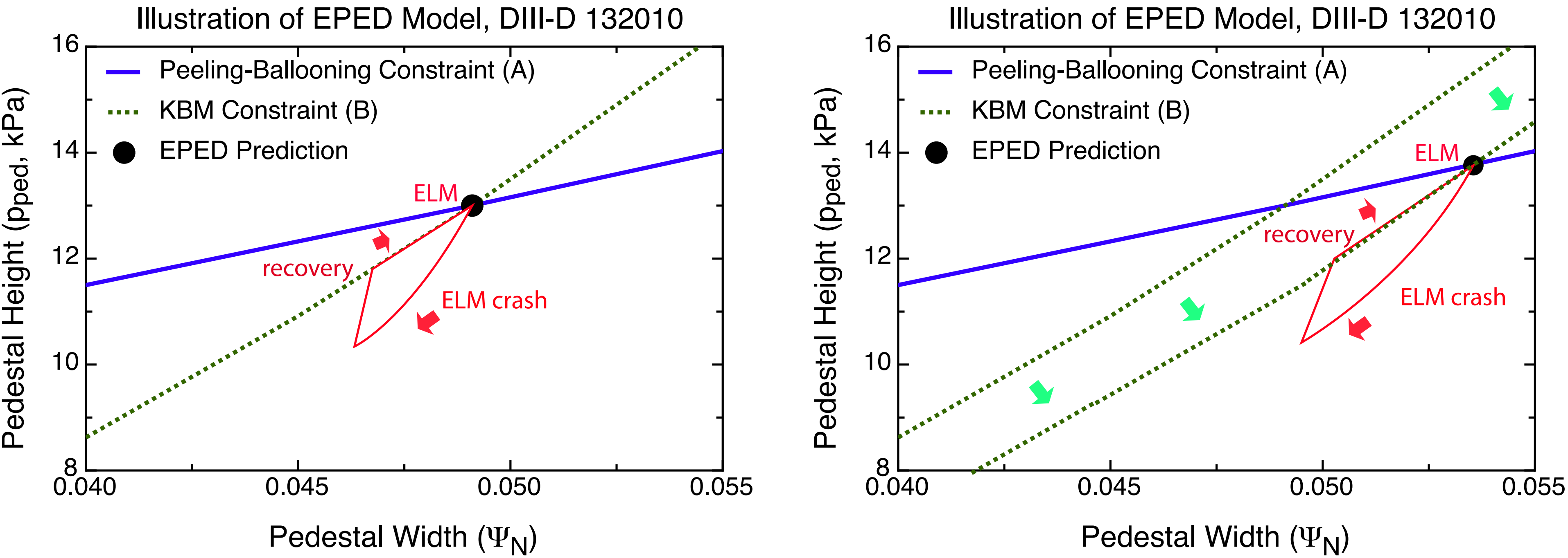
Applying the EPED Model to Develop a Working Model for RMP ELM Suppression





- **When ELMs are suppressed by applied 3D fields (Resonant Magnetic Perturbations or RMPs), the discharges are found to hover in the stable region of the peeling-ballooning stability diagram. WHY? HOW?**
  - Conditions only slightly different between "resonant" ELM suppression, and off-resonant discharges with ELMs (density and gradients similar)
- **Can we understand this in terms of the EPED model?**

The EPED Model and the ELM Cycle

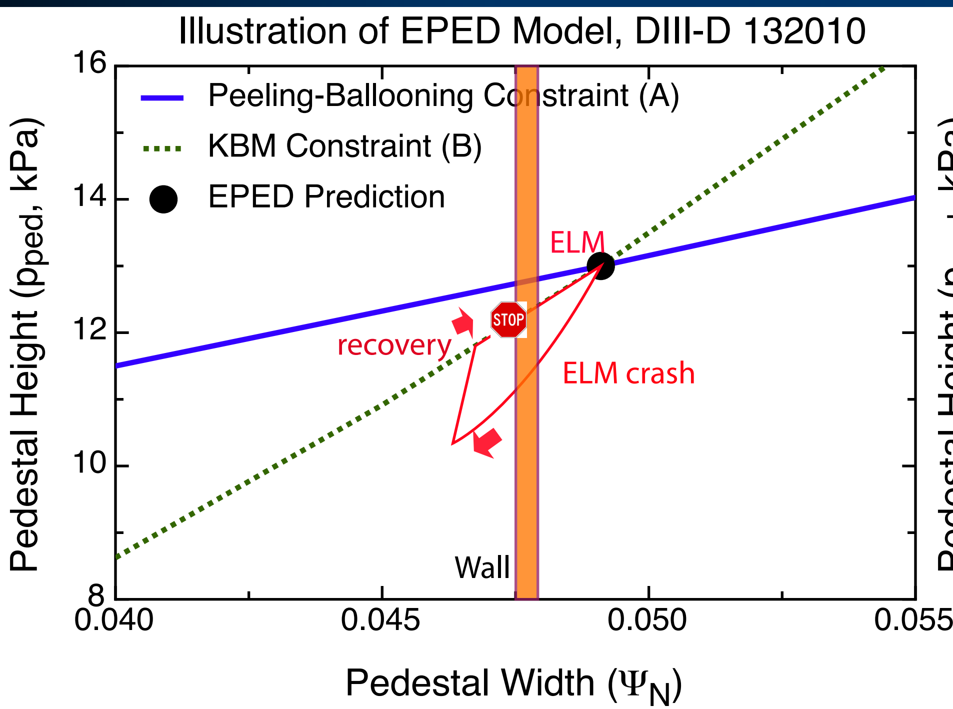


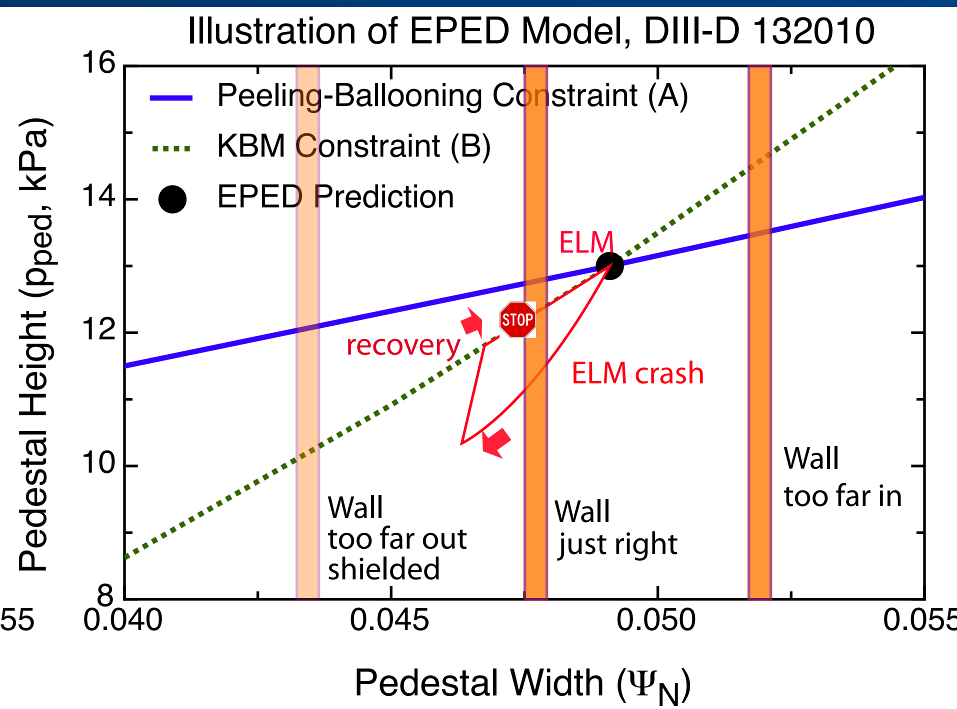
EPED is a static model for the pedestal structure, but can be used to interpret dynamics (zoom in)

- In T1 ELMing discharges, the ELM is triggered by a "global" peeling-ballooning mode (solid blue line), typically followed by a crash, fast recovery (pre-KBM) and slow recovery (with KBM)

Reducing the pressure gradient below the initial KBM limit does NOT, by itself, prevent the ELM (this was hypothesized as how RMP might work, wrong in 2 ways)

A "Wall" Can Stop the ELM ➔RMP q windows





- **Inserting a "wall" that blocks the expansion of the pedestal can stop the recovery and prevent the next ELM**
- **In RMP ELM suppression, this "wall" can be a resonant island or stochastic region that drives strong transport and prevents inward pedestal propagation**
- **Wall location must be precise: too far in will not stop the ELM, too far out will be shielded by very large v_perp_e in the pedestal (2-fluid response physics)**
- **Location of wall determined by q profile ➔ q windows for ELM suppression**

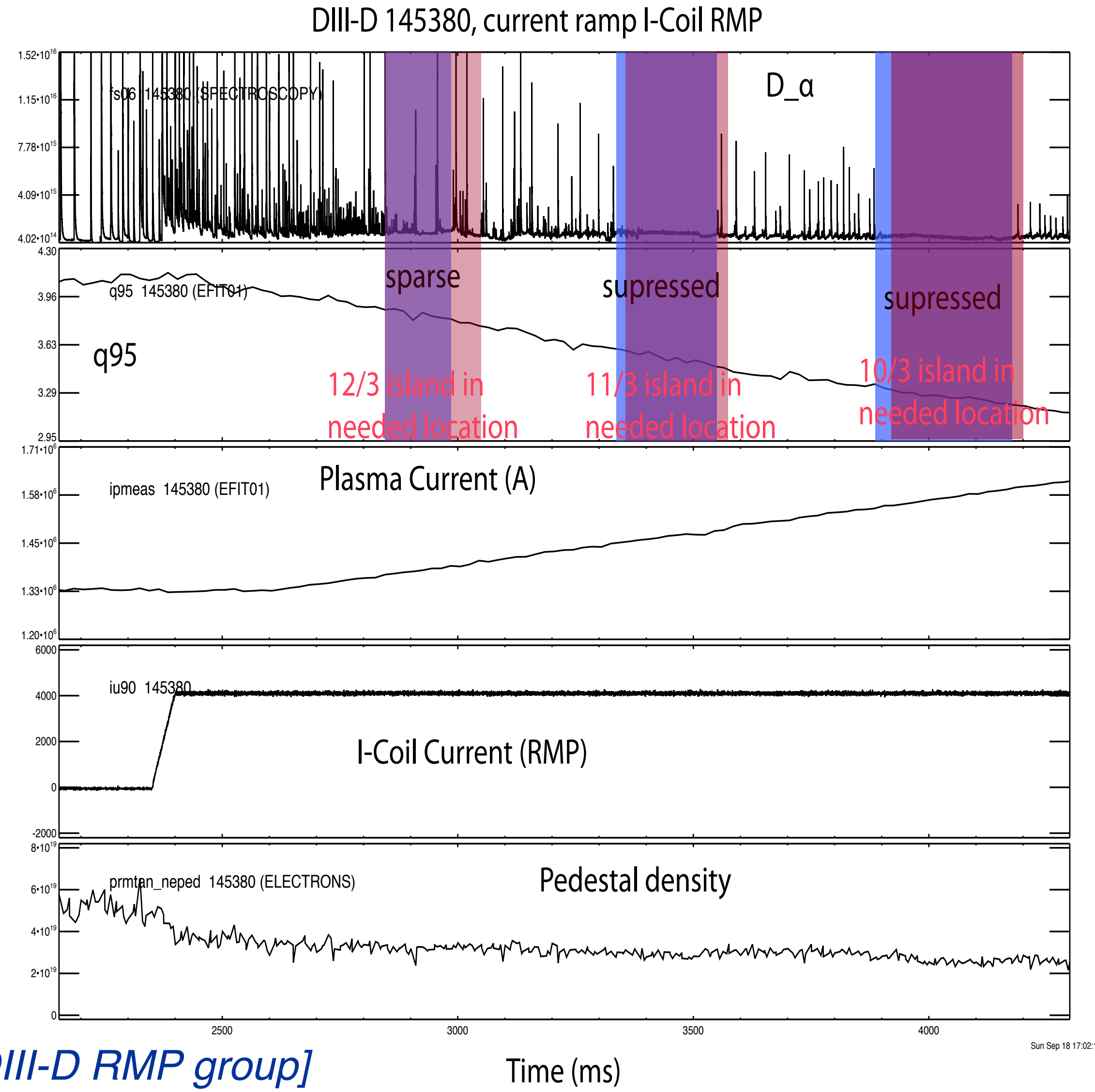
EPED-based Working Model for ELMs Explains Several Observations, Much Work Yet to do

ELM suppression or mitigation seems to occur in q windows which ~correspond to islands in needed location (n=3 RMP)

- DIII-D 145830, I_p ramp, 2 windows of suppression, 1 sparse (blue)
- EPED predicted width 0.03, outer edge of island ~0.97-0.98 (red)

Ubiquity of density pump out (doesn't require precise position of resonant surfaces), and lack of significant change in gradients at ELM suppression also consistent

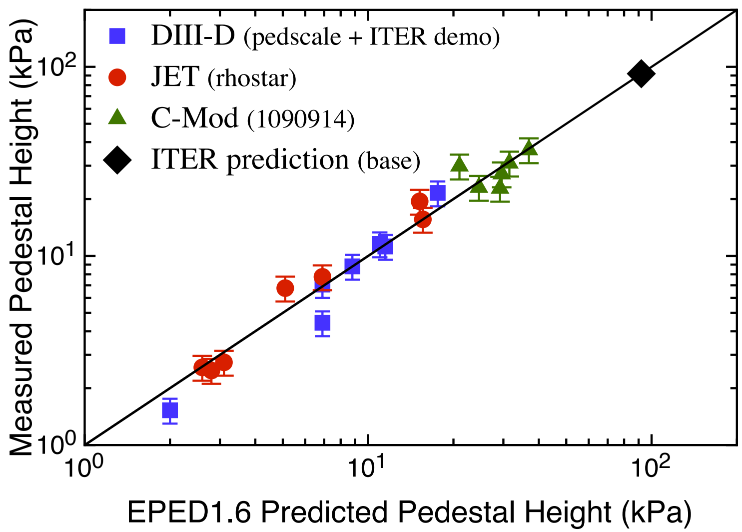
Much work ongoing to further explore, quantify and possibly expand on this working model



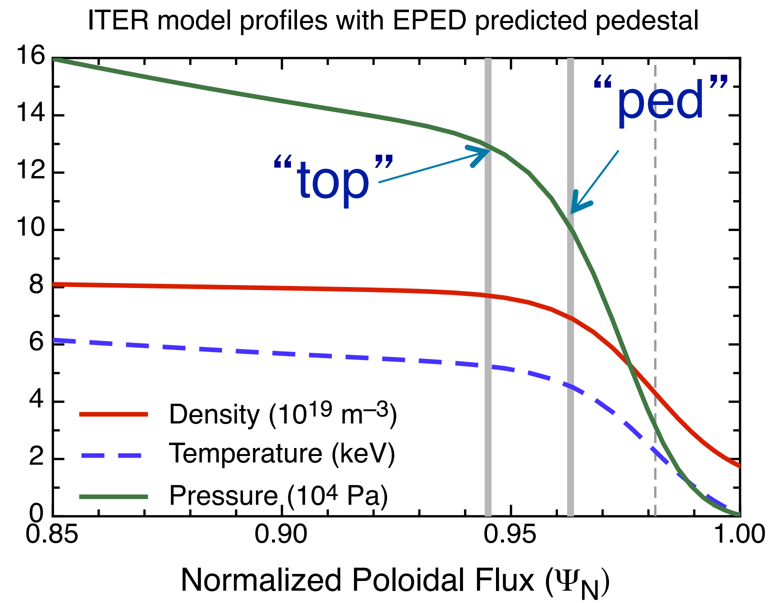
[thanks to D. Orlov, M. Wade, and the DIII-D RMP group]

EPED Predictions and Optimization for ITER

Pedestal Prediction for ITER

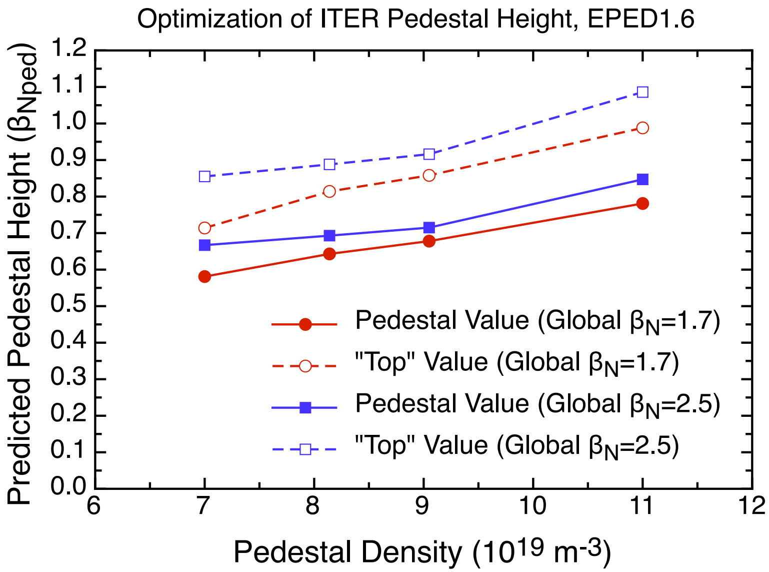


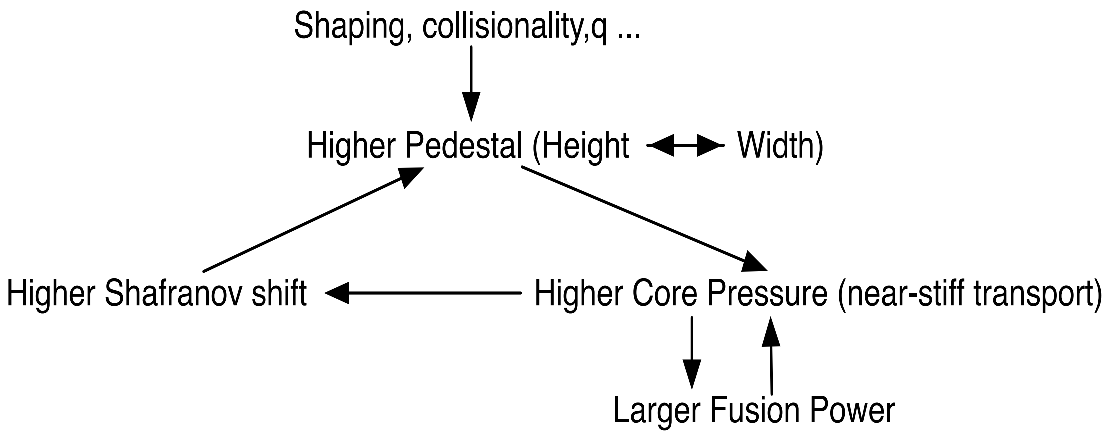
*P.B. Snyder et al NF **51** 103016 (2011)*



- **For ITER baseline, EPED1.6 (full model) predicts a pedestal height of $\beta_{N,ped}$~0.6 and a width Δ_ψ~0.04 (~4.4cm), for n_{ped}~7x10^{19} m^{-3}**
  - In normalized units, values similar to predictions and observations on existing devices
- **Predictions given for pedestal as defined by the tanh function half width ("ped")**
  - To connect to core simulations, we define a pedestal "top" that is another half-width in, inside the sharp gradient region
  - Reference EPED prediction is $\beta_{N,top}$~0.74 at the "top"

Understanding the Pedestal Allows ITER Performance Optimization





- **EPED predicted pedestal height increases with density and Shafranov shift (global β)**
  - Low density kink/peeling regime: *RMP ELM control and Quiescent H-Mode operate in this regime* (not sufficient condition – more research needed)
  - Virtuous cycle: Increasing core pressure improves pedestal height, which in turn increases core pressure **(P_{fus}~p_{ped}^2)**
  - Pedestal top values of $\beta_{N,top}$~0.9 can be achieved with optimization, which allows high predicted global performance in ITER *[Kinsey, NF11]*

Summary: EPED Pedestal Model Developed, Broadly Tested, Used to Study RMP ELM Suppression

- **Predictive model combines non-local Peeling-Ballooning and near-local KBM physics** *P.B. Snyder et al Phys Plas **16** 056118 (2009), NF **49** 085035 (2009), NF **51** 103016 (2011)*
  - Both constraints directly calculated, and each can be independently tested
  - No free or fit parameters, reasonably efficient (~1-20 CPU hrs/case)
- **Model successfully tested against existing machines over a wide range of parameters, including dedicated experiments**
  - Good quantitative agreement found in studies on 5 tokamaks, more than 200 total cases studied with ~20% agreement in height and strong correlation (r>0.8)
  - Test on all 137 JET cases finds ratio of predicted to observed pedestal pressure of 0.97 ± 0.21, with correlation coefficient of 0.86
  - Full EPED1.63 model successfully tested on C-Mod, DIII-D and JET
- **Working model for RMP ELM suppression developing, combining EPED with 2-fluid/kinetic plasma response calculations, may explain several observations, but much work to be done**
- **EPED model used to predict and optimize the pedestal in ITER**
  - Existing tests suggest model should be accurate to roughly ~20%
  - Understanding and optimization of pedestal provides a powerful lever for ITER to achieve and exceed its performance goals ($P_{fus} \sim p_{ped}^2$)